CERN-PH-EP/2012-264
2012/09/21

CMS-TOP-12-017

Search for resonant $t\bar{t}$ production in lepton+jets events in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A model-independent search is presented for the production of heavy resonances decaying into top-antitop quark pairs, seen as excesses above the standard model prediction in the $t\bar{t}$ invariant mass spectrum. Events containing one lepton (muon or electron) and at least two jets are selected from data samples corresponding to 4.4–5.0 fb⁻¹ of integrated luminosity collected by the CMS experiment in pp collisions at $\sqrt{s} = 7$ TeV at the LHC. Results are presented from the combination of two dedicated searches optimized for boosted production and production at threshold. No excess of events is observed over the expected yield from the standard model processes. Top-color Z' bosons with narrow (wide) width are excluded at 95% confidence level for masses below 1.49 (2.04) TeV and an upper limit of 0.3 (1.3) pb or lower is set on the production cross section times branching fraction for resonance masses above 1 TeV. Kaluza–Klein excitations of a gluon with masses below 1.82 TeV (at 95% confidence level) in the Randall–Sundrum model are also excluded, and an upper limit of 0.7 pb or lower is set on the production cross section times branching fraction for resonance masses above 1 TeV.

Submitted to the Journal of High Energy Physics

*See Appendix A for the list of collaboration members

1 Introduction

The top quark is the heaviest known fermion, making it a powerful benchmark to extend our understanding of the origin of mass. Because of its large mass, the top quark plays a central role in several theories beyond the standard model (SM). These theories predict the existence of heavy resonances that manifest themselves as an additional resonant component to the SM $t\bar{t}$ production. Examples of such resonances, which decay preferentially into $t\bar{t}$, include models with massive color-singlet Z-like bosons in extended gauge theories [1–3], colorons [4–7] or axigluons [8, 9], models in which a pseudoscalar Higgs boson may couple strongly to top quarks [10], and models with extra dimensions, such as Kaluza–Klein (KK) excitations of gluons [11] or gravitons [12] in various extensions of the Randall–Sundrum model [13].

Recent models [14–18] aimed at explaining the $t\bar{t}$ charge asymmetry observed at the Tevatron [19–22] predict resonances in the 0.7–3 TeV mass range with production cross sections of the order of a few pb and add renewed interest to the sub-TeV mass region. Independent of the exact model, resonant $t\bar{t}$ production could be visible in the reconstructed invariant mass spectrum ($M_{t\bar{t}}$).

Searches performed at the Tevatron have set upper limits on the production cross section of narrow resonances (Z' with mass below ~ 900 GeV) decaying into $t\bar{t}$ [23–28]. Similarly, searches at the Large Hadron Collider (LHC) have set sub-pb limits on the production cross section of resonances in the 0.5–3 TeV mass range [29–31].

In this paper, we present a model-independent search for the production of heavy resonances decaying into $t\bar{t}$ using data collected by the Compact Muon Solenoid (CMS) experiment in pp collisions at $\sqrt{s} = 7$ TeV at the LHC. Using samples corresponding to an integrated luminosity of 4.4–5.0 fb $^{-1}$, we focus on the semileptonic $t\bar{t}$ decay mode $t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (q_1\bar{q}_2b)(\ell^-\bar{\nu}_\ell\bar{b})$ (or charge conjugate) wherein one W boson decays to an electron or muon and a neutrino, and the other decays hadronically. The range of 0.5–3 TeV in $M_{t\bar{t}}$ is covered by the combination of two dedicated searches: one optimized for resonances with masses smaller than 1 TeV (threshold region), and a second one optimized for masses larger than 1 TeV (boosted region). Both regions increase the sensitivity of the search by identifying jets originating from the hadronization of b quarks (b jets), and separating the samples into various categories depending on the lepton flavor, the number of jets, and the number of b jets. The resulting samples are dominated by SM $t\bar{t}$ and W bosons produced in association with jets. A limit on the production cross section of heavy resonances is extracted by performing a template-based statistical evaluation of the reconstructed $M_{t\bar{t}}$ distribution.

The CMS detector is briefly described in Section 2. Section 3 provides details on the data and simulated samples used in the analyses. Sections 4 and 5 describe the event selection and the $t\bar{t}$ event reconstruction, respectively. The main sources of systematic uncertainty in the analyses are described in Section 6. Results are shown in Section 7 and a summary is provided in Section 8.

2 The CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged particle trajectories are measured by the silicon pixel and strip trackers, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle of the trajectory

of the particle with respect to the counterclockwise beam direction. A crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter surround the tracking volume. In this analysis the calorimetry provides high-resolution energy and direction measurements of electrons and hadronic jets. Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid. The detector is nearly hermetic, allowing for momentum balance measurements in the plane transverse to the beam directions, which are used to infer the presence of neutrinos in events. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A more detailed description of the CMS detector can be found in Ref. [32].

3 Data and Simulated Samples

The data analyzed for the threshold analyses were recorded with triggers requiring a single isolated (defined in Section 4.1) muon or electron with a transverse momentum (p_T) threshold of 17 GeV or 25 GeV, respectively, in combination with a number of jets with a p_T threshold of 30 GeV. Events containing an electron were required to have three or more jets throughout the data-taking period, while the minimum number of jets in events containing a muon increased from zero to three as the instantaneous luminosity increased. The data analyzed for the boosted analyses were recorded with triggers requiring one muon with a p_T threshold of 40 GeV or one electron with a p_T threshold of 65 GeV, with no isolation requirements on the leptons. To avoid too high a trigger rate, the electron trigger was prescaled for the highest instantaneous luminosities. This resulted in a loss of 0.6 fb^{-1} of integrated luminosity for the boosted electron analysis compared to the other channels. No additional requirements were made on the jets or missing transverse energy in the triggers used for the boosted analyses.

Offline, we use a particle-flow [33] based event reconstruction, which combines information from each subdetector, including charged particle tracks from the tracking system and deposited energy from the electromagnetic and hadronic calorimeters, to reconstruct all particles in the event. Particles are classified as electrons, muons, photons, charged hadrons, and neutral hadrons. Particles identified as originating from multiple primary collisions at high instantaneous luminosity (pileup) are removed from the event.

Muons are reconstructed using the information from the muon chambers and the tracking detectors [34]. Tracks are required to have at least 11 hits including at least one in the pixel layers. The tracks must also pass within 0.02 cm of the beam spot in the plane transverse to the beam, and within 1 cm along the beam axis.

Electron candidates are initially identified by matching a track to a cluster of energy in the electromagnetic calorimeter. Candidates are selected [35] using shower-shape information, the quality of the track and the spatial match between the track and electromagnetic cluster, the fraction of total cluster energy in the hadronic calorimeter, and the amount of activity in the surrounding regions of the tracker and calorimeters. Electrons coming from photon conversions in the detector material are rejected if there are missing hits in the inner tracker layers or if there is another close track with opposite charge and with a similar polar angle.

Jets are reconstructed by clustering the particle-flow candidates not identified as leptons using an anti- k_T algorithm with a distance parameter $R = 0.5$ [36]. Corrections are applied to account for the dependence of the detector response to jets as a function of η and p_T [37] and the effects of pileup. The jets associated to b quarks are identified using an algorithm that reconstructs the secondary vertex corresponding to the decay of a B hadron. When no secondary vertex is found, the significance of the impact parameter with respect to the primary vertex of the

second most displaced track is used as a discriminator to distinguish decay products of a B hadron from prompt tracks [38].

The negative of the vector sum of the momenta of all reconstructed particles in the plane transverse to the beam is the missing transverse momentum [39], with magnitude denoted by missing transverse energy E_T^{miss} .

The SM background processes are simulated by MADGRAPH 5.1.1 [40], PYTHIA 6.4.24 [41], and POWHEG [42] event generators using CTEQ6L parton distribution functions of the proton [43]. The generated events are subsequently processed with PYTHIA to provide the showering of the partons and fully simulated with CMS software based on GEANT4 [44, 45].

The W boson and Drell–Yan production in association with up to four jets are simulated with MADGRAPH, with additional jet production described via matrix elements matched to parton showers using the MLM prescription [46] with a matching threshold of 20 GeV. The next-to-next-to-leading order (NNLO) production cross sections times branching fractions into leptons (electrons, muons and taus) are used [47]: 31.3 nb for W, and 3.05 nb for Drell–Yan production of dilepton final states with invariant mass > 50 GeV. The background from Drell–Yan production of dilepton final states with invariant mass < 50 GeV is negligible. The contribution from QCD multijet processes is obtained directly from data.

The SM $t\bar{t}$ events are generated with MADGRAPH, assuming a top-quark mass of 172.5 GeV. Higher-order gluon and quark production is described by the matrix elements with up to three extra partons beyond the $t\bar{t}$ system. The chosen threshold for the matching is 40 GeV, which ensures a smooth transition from the matrix element to the parton showering description. An additional $t\bar{t}$ sample is generated using POWHEG to provide a cross-check and to estimate systematic uncertainties in the modeling. The inclusive $t\bar{t}$ cross section value of 157.5 pb is used [48, 49].

Single top-quark production is modeled in POWHEG. The approximate NNLO cross sections of 42 pb and 3.2 pb are used for t -channel and s -channel single top-quark production, respectively, along with the corresponding single \bar{t} -quark production cross sections of 23 pb and 1.4 pb. The approximate NNLO value of 7.9 pb is used for Wt and $W\bar{t}$ associated production [50–52].

Finally, as reference models for new physics, we use the sequential standard model (SSM) top-color Z' bosons with a natural width $\Gamma_{Z'}$ equal to 1.2% (narrow width) and 10% of the Z' mass $m_{Z'}$ based on [4–7] and KK gluons based on [11]. Signal samples are generated with PYTHIA 8.145 with a range of masses between 500 GeV and 3 TeV. Only decays into $t\bar{t}$ are simulated in the Z' samples. The KK gluons are simulated with branching fractions to $t\bar{t}$ of 0.93, 0.92, 0.90, and 0.87 for resonance masses of 1, 1.5, 2 and 3 TeV.

4 Event Selection

To study the range of 0.5–3 TeV in $M_{t\bar{t}}$, two complementary strategies are pursued: firstly, the threshold search focuses on the 0.5–1 TeV mass range using criteria optimized to identify top quarks produced with a small boost in the detector frame and hence with well-separated decay products. In this region, if all decay products are reconstructed within the kinematic acceptance, we expect the final state to contain exactly one isolated lepton, four jets produced by the four quarks (two of which are b jets) in the semileptonic $t\bar{t}$ decay, and E_T^{miss} .

Secondly, for resonance masses above 1 TeV, the highly Lorentz-boosted top quarks will yield collimated decay products that are partially or fully merged. This can be seen in Fig. 1, which

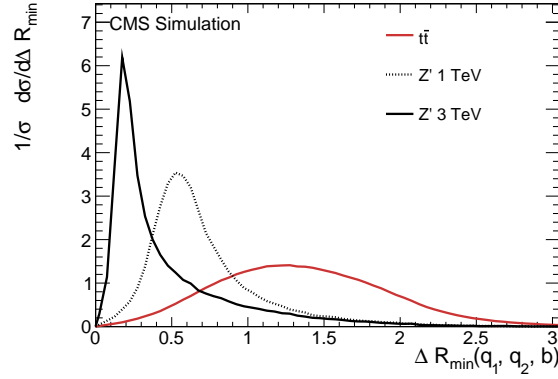


Figure 1: The distribution of the minimum ΔR of all three possible pairings between the three quarks (q_1, q_2, b) of the hadronic top-quark decay for SM $t\bar{t}$ production and two different Z' mass hypotheses. For events with ΔR_{\min} smaller than the parameter $R = 0.5$ in the jet clustering, jets merge and fewer than three jets are reconstructed.

shows that in the boosted region the angular distance between the partons is smaller than the jet clustering distance parameter. As a consequence, the products of the hadronically decaying top quark might be reconstructed as fewer than three jets, and the leptons might not be isolated. The boosted search thus selects events containing one electron or muon with no isolation requirement and at least two jets.

4.1 Threshold analyses

We select events containing either one isolated muon with $p_T > 20$ GeV and $|\eta| < 2.1$, or one isolated electron with $p_T > 30$ GeV and $|\eta| < 2.5$. The isolation requirement is based on the ratio of the total transverse energy observed from all hadrons and photons in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$ around the lepton direction to the transverse momentum of the lepton itself. This quantity is required to be less than 0.125 for muons and less than 0.1 for electrons. Events with two isolated lepton candidates are vetoed to reduce the background from Drell-Yan and $t\bar{t}$ production in which both W bosons decay leptonically.

Events are further required to contain at least three jets with $|\eta| < 2.4$ and $p_T > 50$ GeV, and additional jets with $|\eta| < 2.4$ and $p_T > 30$ GeV, if any. To enhance the rejection of background from W-boson and Drell-Yan production in association with relatively low- p_T jets, the leading jet is required to have $p_T > 70$ GeV. Multijet background is suppressed further by requiring $E_T^{\text{miss}} > 20$ GeV. The fraction of simulated semileptonic signal events passing this selection varies from 16 to 35% for resonance masses below 1 TeV.

Events are then separated into eight categories according to the lepton flavor (electron or muon), the number of jets, and the number of b-tagged jets. The categories defined by jets are: events with three jets, of which at least one is b tagged; events with four or more jets, of which none is b tagged; events with four or more jets, of which exactly one is b tagged; and events with four or more jets, of which at least two are b tagged.

4.2 Boosted analyses

We select events containing either one muon with $p_T > 42$ GeV and $|\eta| < 2.1$, or one electron with $p_T > 70$ GeV and $|\eta| < 2.5$, and at least two jets with $|\eta| < 2.4$ and $p_T > 50$ GeV. The leading jet p_T lower threshold is set to 250 GeV (150 GeV) in the muon (electron) channel. No isola-

tion requirement is applied to the leptons. Multijet background is reduced with a requirement on the ΔR separation in the 2D plane: $\Delta R(\text{lepton, closest jet}) > 0.5$ or $p_T^{\text{rel}}(\text{lepton, closest jet}) > 25 \text{ GeV}$. Here, p_T^{rel} is defined as the magnitude of the lepton momentum orthogonal to the closest jet axis, where any jet with $p_T > 25 \text{ GeV}$ is considered. We also require the scalar quantity $L_T > 150 \text{ GeV}$, where $L_T = E_T^{\text{miss}} + p_T^{\text{lepton}}$.

In the electron channel only, the multijet background is further reduced by requiring that $E_T^{\text{miss}} > 50 \text{ GeV}$ and applying a series of topological requirements that ensure the missing transverse momentum does not point along the transverse direction of the electron (e) or of the leading jet (j):

$$-\frac{1.5}{75 \text{ GeV}} E_T^{\text{miss}} + 1.5 < \Delta\phi\{(\text{e or j}), E_T^{\text{miss}}\} < \frac{1.5}{75 \text{ GeV}} E_T^{\text{miss}} + 1.5.$$

Even though the lepton p_T requirements are dictated by the trigger threshold, the leading jet p_T requirement is chosen so that the total transverse energy of the event (including E_T^{miss}) is as close as possible in both channels. In addition, we ensure the two channels contain no overlap with each other by vetoing events that contain a second lepton.

Events are separated into four categories according to the lepton flavor (electron or muon) and the number of b-tagged jets: either no b-tagged jets, or at least one b-tagged jet. The fraction of simulated semileptonic signal events passing this selection varies from 13 to 24% for resonance masses between 1 and 3 TeV.

5 The $t\bar{t}$ Event Reconstruction

The four-vectors of the top quark and antiquark candidates are reconstructed by assigning the final state objects in each event to either the leptonic or the hadronic leg of the $t\bar{t}$ pair decay. We then choose between the possible hypotheses using the criteria described below that depend on the number of reconstructed jets. This $t\bar{t}$ reconstruction process results in a unique value for the reconstructed $M_{t\bar{t}}$ for each event.

First, the charged lepton and the E_T^{miss} are assigned to the leptonic leg, where E_T^{miss} is interpreted as the transverse component of the momentum of the neutrino. Imposing the condition that the invariant mass of the lepton and neutrino is equal to the mass of the W boson (80.4 GeV) allows the construction of a quadratic equation for the longitudinal component of the momentum of the neutrino. In the absence of a real solution, the boosted analyses retain the real part of the complex solution. The threshold analyses modify the components of E_T^{miss} by the minimal amount in $|\Delta E_T^{\text{miss}}|_x + |\Delta E_T^{\text{miss}}|_y$ to give one real solution, which results in an improved mass resolution. If there are two real solutions, hypotheses are built for both cases, effectively doubling the number of combinations for that event.

For events with four or more jets in the threshold analyses, the choices of neutrino solution and jet association are made simultaneously by forming a χ^2 from the sum of the normalized squared deviations of the leptonic top-quark mass, hadronic top-quark mass, hadronic W mass, p_T of the $t\bar{t}$ system, and the ratio of the p_T of the four selected jets to the p_T of all jets in the event. The central values and widths used are obtained from the distributions of these quantities in the Monte Carlo simulation. The χ^2 is calculated for each possible combination, including the two neutrino solutions if they are both physical. The b-tagged jets may only be associated to a b quark in the decay chain, thereby reducing the number of possible combinations. For each event, the combination with the smallest value of χ^2 is chosen. The association of jets to the W

boson and the b quarks is found to be correct in approximately 80% of simulated $t\bar{t}$ events for which the four jets in the decay chain are reconstructed.

For events with only three jets in the threshold analyses, it is assumed that two jets from the $t\bar{t}$ decay may have merged. The leptonic W boson is first reconstructed as described above. The solution for the longitudinal neutrino momentum is chosen to give the closest match to the leptonic top-quark mass when the leptonic W boson is combined with any of the three jets. The invariant mass of the leptonic W and all three jets together is then taken as an estimate of $M_{t\bar{t}}$.

For the boosted analyses, we allow for collimated decay products that are partially or fully merged by considering all hypotheses that have exactly one jet assigned to the leptonic leg, and at least one jet assigned to the hadronic leg. A two-term χ^2 is constructed from the sum of the normalized squared deviations of the leptonic top-quark mass and the hadronic top-quark mass. For each event, the combination with the smallest value of χ^2 (labeled χ^2_{\min}) is chosen. Next, the event selection described in Section 4.2 is extended by applying additional conditions that improve the overall sensitivity of the boosted analyses. For the electron channel only, the transverse momentum of the reconstructed leptonic top quark is required to be greater than 100 GeV. We require $\chi^2_{\min} < 8$ for both channels. This value is chosen such that the efficiency for this cut is 50% for signal and approximately 10% for the W +jets background. Finally, we categorize events according to the number of b -tagged jets as either with no b -tagged jets, or with at least one b -tagged jet.

For the threshold analyses, the multijet background contribution in each of the categories is determined by defining two control regions in data. The first contains events with the same lepton isolation requirement as the signal (less than 0.1) but with the E_T^{miss} requirement inverted (i.e. less than 20 GeV). The second multijet-dominated region contains events with either a muon with the isolation value between 0.2 and 0.5 and no E_T^{miss} requirement, or an electron candidate that has been rejected as consistent with being a photon conversion. The distribution of a chosen variable in the multijet-dominated region is used to define a template. This template is fitted to the distribution in the low- E_T^{miss} region together with a template for the distribution of other backgrounds taken from simulation. The chosen variable is selected based on both its power to discriminate between the contributions and the reliability of its modeling in simulation. For muon events the p_T of the vector sum of the jet momenta is used, whereas for electron events the reconstructed electron η is used. This provides the multijet background yield in the low- E_T^{miss} control region, which is then used to extrapolate into the signal region with the relative yields below and above E_T^{miss} of 20 GeV in the second control region. The second control region is also used to define the $M_{t\bar{t}}$ shape of the multijet background contribution to each category. In the boosted analyses, the multijet contamination after the final selection is found to be negligible.

The numbers of expected and observed events in each analysis channel for the threshold and boosted analyses are summarized in Tables 1 and 2, respectively. The Z' samples are normalized arbitrarily to cross sections times branching fractions of 1 pb. For the threshold analyses, the simulated samples are normalized to theoretical predictions. For the boosted analyses, the yields of the simulated samples are normalized to data using scale factors derived in a maximum likelihood fit to the $M_{t\bar{t}}$ distribution in both channels simultaneously, as described in Section 7. Figures 2 and 3 show the $M_{t\bar{t}}$ distributions for the threshold and boosted analyses, respectively. Figure 3 also shows the distribution of the number of jets in the events for the boosted analyses. It can be observed that, in the boosted region, the signal populates the 2-jet bin while the SM background has larger jet multiplicity. Good agreement is observed in all cases between data and the SM predictions.

Table 1: Number of expected and observed events in the threshold analyses for an integrated luminosity of 5.0 fb^{-1} . The narrow-width Z' samples are normalized to cross sections times branching fractions of 1 pb. The other simulated samples are normalized to theoretical predictions. The uncertainty in the total background corresponds to yield changes originating from the systematic uncertainties associated with the jet energy corrections, jet energy resolutions, b tagging, and pileup. The statistical uncertainties for the simulated samples are negligible.

Threshold analyses, muon channel				
Sample	$N_{\text{jet}} = 3$	$N_{\text{jet}} \geq 4$	$N_{\text{jet}} \geq 4$	$N_{\text{jet}} \geq 4$
	$N_{\text{b-tag}} \geq 1$	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} = 1$	$N_{\text{b-tag}} \geq 2$
Z' (M=0.5 TeV)	48.5	14.0	41.1	34.6
Z' (M=1.0 TeV)	68.5	36.1	95.5	74.7
Z' (M=1.5 TeV)	56.4	33.9	76.5	50.9
Z' (M=2.0 TeV)	38.0	32.4	60.7	37.5
$t\bar{t}$	5612	2988	7802	6093
W/Z+jets	1727	7705	1296	173
Single top	550	202	423	228
Multijet	164	195	104	152
Total background	8052 ± 511	11089 ± 1241	9626 ± 822	6646 ± 687
Data	8465	10714	9664	6697

Threshold analyses, electron channel				
Sample	$N_{\text{jet}} = 3$	$N_{\text{jet}} \geq 4$	$N_{\text{jet}} \geq 4$	$N_{\text{jet}} \geq 4$
	$N_{\text{b-tag}} \geq 1$	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} = 1$	$N_{\text{b-tag}} \geq 2$
Z' (M=0.5 TeV)	34.7	10.5	29.4	25.0
Z' (M=1.0 TeV)	58.9	32.4	85.0	67.4
Z' (M=1.5 TeV)	51.2	31.7	73.5	50.8
Z' (M=2.0 TeV)	33.8	30.2	59.5	37.6
$t\bar{t}$	4307	2395	6183	4770
W/Z+jets	1372	6355	1051	142
Single top	428	158	345	184
Multijet	491	1398	504	210
Total background	6597 ± 442	10307 ± 1136	8083 ± 721	5306 ± 514
Data	6932	10008	7946	5309

Table 2: Number of expected and observed events in the boosted analyses for an integrated luminosity of $4.4\text{--}5.0\text{ fb}^{-1}$. The narrow-width Z' samples are normalized to cross sections times branching fractions of 1 pb. The other simulated samples are normalized to data, see Section 7. The uncertainty in the total background corresponds to yield changes originating from the systematic uncertainties associated with the jet energy corrections, jet energy resolutions, b tagging, and pileup. The statistical uncertainties for the simulated samples are negligible.

Boosted analyses Sample	Electron channel		Muon channel	
	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} \geq 1$	$N_{\text{b-tag}} = 0$	$N_{\text{b-tag}} \geq 1$
Z' ($M = 1\text{ TeV}$)	17.1	36.5	27.8	48.3
Z' ($M = 1.5\text{ TeV}$)	44.7	55.4	95.9	94.4
Z' ($M = 2\text{ TeV}$)	62.1	52.8	146.3	94.1
Z' ($M = 3\text{ TeV}$)	57.2	36.9	155.2	69.0
$t\bar{t}$	172	336	157	262
W/Z +jets	95	6	149	9
Single top	9.3	15	8.1	11
Total background	276 ± 58	357 ± 50	314 ± 72	282 ± 34
Data	277	354	300	269

6 Systematic Uncertainties

Systematic uncertainties enter the analyses in two ways: those related to the total normalization of the simulated samples, and those from the effects that change both the normalization and shape of the background and expected signal distributions.

Normalization uncertainties on the theoretical production cross sections are considered for all background processes. In some instances, larger uncertainties are used for the boosted analyses as they probe a limited region of phase space. The following variations on the rates, which were obtained in a previous analysis [53], are included: $t\bar{t}$ (15%); single top-quark for threshold (30%) and for boosted (50%) analyses; W/Z +light-quark jets correlated (50%) and additional Drell-Yan uncorrelated (30%) for threshold analyses, W +light-quark jets (50%) and uncorrelated Z +light-quark jets (100%) for boosted analyses; W/Z +heavy-quark jets (100%). In addition, a 2.2% uncertainty in the luminosity [54] and 3% (5%) lepton trigger and identification uncertainty is applied to all simulated samples for the threshold (boosted) analyses.

Several sources of systematic uncertainty affect both the shape and the rate of the templates used in the analyses. The uncertainty on the energy of jets is of the order of a few percent and is parametrized as a function of the jet p_T and η [37]. The uncertainty on the jet energy resolution varies from 6 to 20% depending on the jet η . The effect of both variations is propagated to the event E_T^{miss} . The uncertainty on the b-tagging efficiency for b jets ranges from 1.6 to 8% depending on the jet η and is doubled for b jets with $p_T > 670\text{ GeV}$ [38]. The uncertainty on the b-tagging efficiency for c jets is taken as twice the uncertainty for b jets. The uncertainty for all other jets (mistag rate) is 11%.

Some of the theoretical uncertainties affect the normalization and shape of the simulated samples. A simultaneous variation of the factorization and renormalization scales to half and twice the nominal scales is allowed for the $t\bar{t}$ and W +jets samples. The matrix element to parton shower matching threshold and the amount of initial- and final-state radiation are also allowed to vary for these samples. A further uncertainty is included as the difference between the $t\bar{t}$

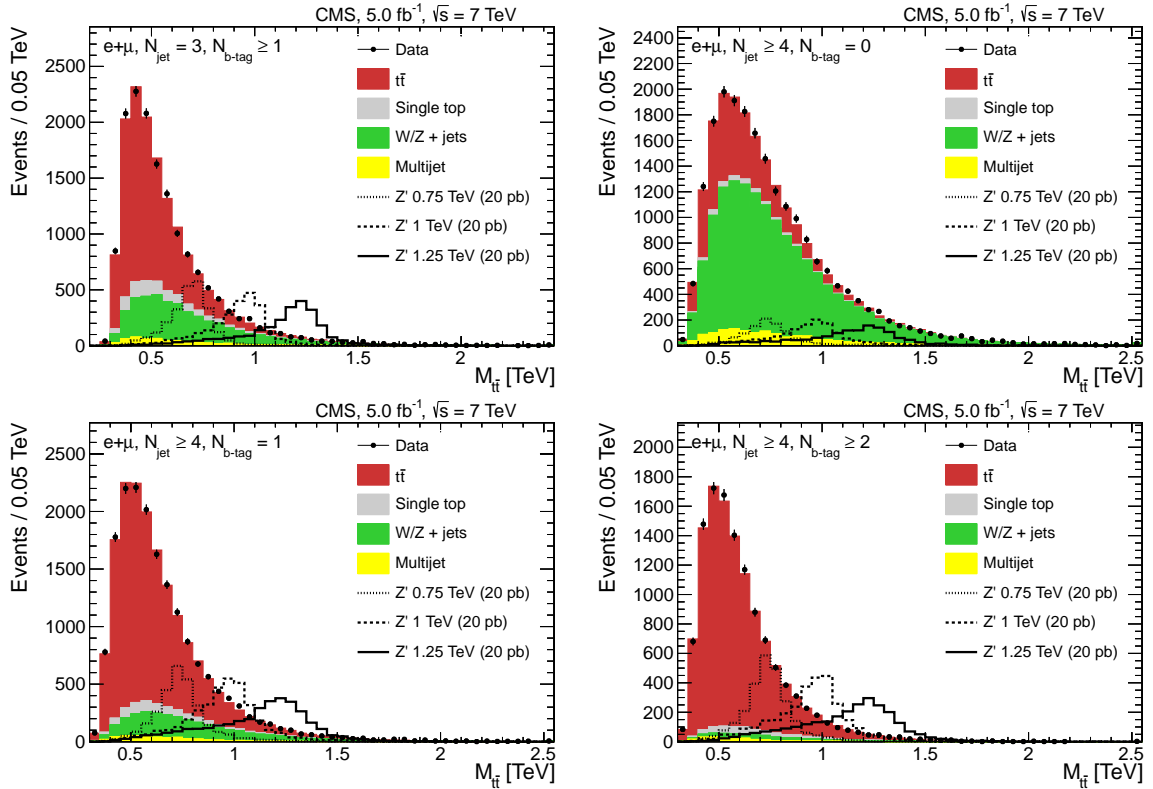


Figure 2: Comparison of the reconstructed $M_{t\bar{t}}$ in data and SM predictions for the threshold analysis with (a) 3 jets of which ≥ 1 b tagged, (b) 4 jets, none of which is b tagged, (c) 4 jets of which one is b tagged, (d) 4 jets of which ≥ 2 are b tagged. Expected signal contributions for narrow-width topcolor Z' models at different masses are also shown. For clarity, a cross section times branching fraction of 20 pb is used for the normalization of the Z' samples.

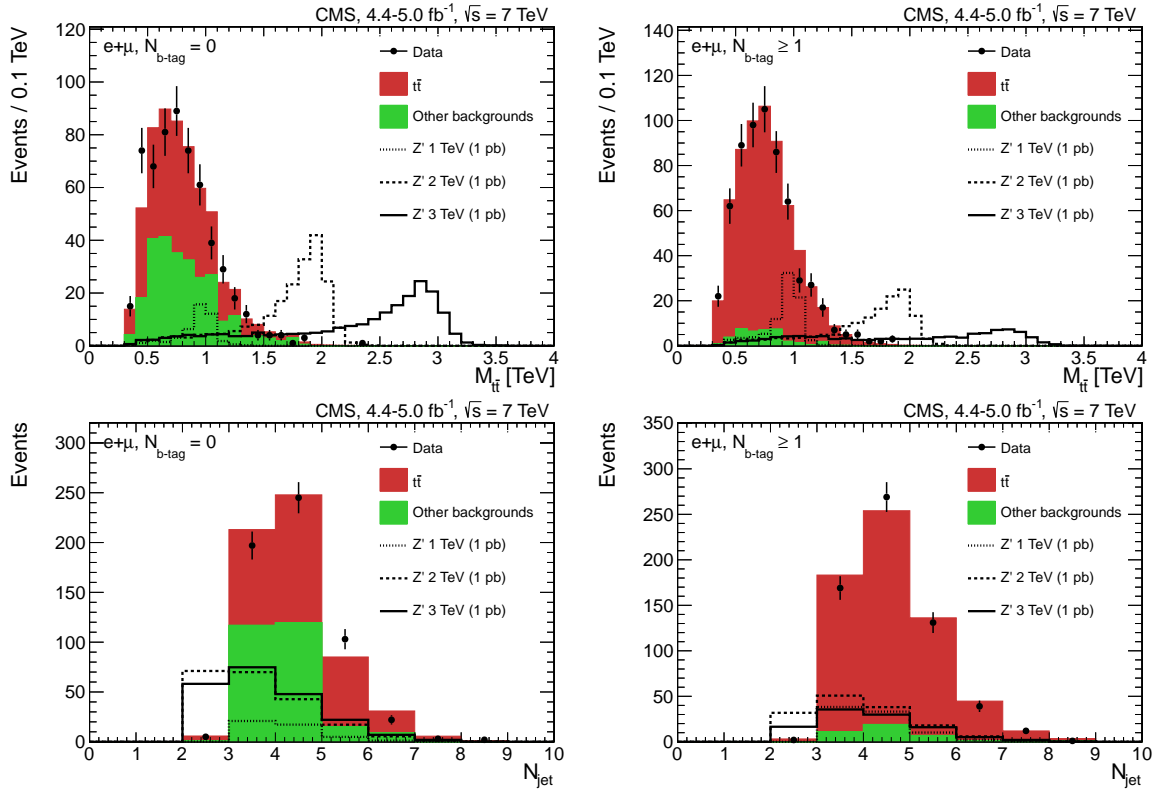


Figure 3: Comparison of the reconstructed $M_{t\bar{t}}$ in data and SM predictions for the boosted analysis with (a) no b -tagged jets, (b) ≥ 1 b -tagged jets. Comparison of the jet multiplicity distribution in data and SM background predictions for the boosted analysis with (c) no b -tagged jets, (d) ≥ 1 b -tagged jets. Expected signal contributions for narrow-width topcolor Z' models at different masses are also shown. A cross section times branching fraction of 1.0 pb is used for the normalization of the Z' samples.

production models in POWHEG and MADGRAPH. For all simulated samples, the minimum bias cross section is varied by 1 standard deviation of its measured value to account for the effect of pileup.

7 Results

The statistical analysis is based on a binned likelihood of the $M_{t\bar{t}}$ distributions in the considered channels, i.e., eight channels for the threshold analyses and four channels for the boosted analyses. The number of events in bin i is assumed to follow a Poisson distribution with mean λ_i , given by the sum over all considered background processes and the Z' signal. The signal is scaled with a signal strength modifier μ , which is the signal cross section in pb:

$$\lambda_i = \mu S_i + \sum_k B_{k,i}.$$

Here, k runs over all considered background processes, B_k is the background template for background k , and S is the signal template, scaled according to luminosity and a signal cross section of 1 pb.

The presence of systematic uncertainties affects the yields λ_i . A nuisance parameter θ_u is thus introduced for each independent source of systematic uncertainty considered. A rate-only uncertainty is modeled with a coefficient for the template B_k with a log-normal prior. A rate and shape uncertainty is modeled by choosing a Gaussian prior for θ_u and using this parameter to interpolate between the nominal template and the shifted templates obtained by applying a $\pm 1 \sigma$ systematic shift to the simulated samples. This interpolation uses a smooth function, which is cubic in the range $\pm 1 \sigma$ and linear beyond $\pm 1 \sigma$.

To set exclusion limits on a Z' hypothesis, we define a test statistic q_μ , which depends on the hypothesized signal rate μ [55]:

$$q_\mu = -2 \ln \frac{\mathcal{L}(\hat{\theta}_\mu, \mu | \text{data})}{\mathcal{L}(\hat{\theta}, \hat{\mu} | \text{data})},$$

where $\hat{\theta}_\mu$, $\hat{\mu}$, and $\hat{\theta}$ are the values of the parameters θ and μ that maximize the likelihoods in the numerator and denominator, and the subscript μ in $\hat{\theta}_\mu$ indicates that the maximization of the likelihood in the numerator is done under the hypothesis of a signal of strength μ . One-sided limits on the Z' production rate are obtained by constraining $\hat{\mu} \leq \mu$ in the denominator.

We use the modified frequentist construction CL_s [56, 57] to calculate the 95% confidence level (CL) upper limits on the $Z' \rightarrow t\bar{t}$ cross section. We define two tail probabilities associated with the observed data; the probability to obtain a value for the test statistic q_μ larger than the observed value q_μ^{obs} for the signal+background, and for the background-only hypotheses:

$$\begin{aligned} \text{CL}_{s+b} &= P(q_\mu \geq q_\mu^{\text{obs}} | \theta, \mu) \\ \text{CL}_b &= P(q_\mu \geq q_\mu^{\text{obs}} | \theta, \mu = 0) \end{aligned}$$

and obtain CL_s from the ratio

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b}.$$

To quote the upper limit on μ at the 95% confidence level, we adjust μ until we reach $\text{CL}_s = 0.05$.

The expected upper limits are calculated using background-only pseudo-experiments ($\mu = 0$) and calculating the upper limit for each pseudo-experiment. The expected limit is given by the median of the distribution of upper limits, and the central 68% and 95% give the ± 1 and ± 2 standard deviation (s.d.) excursions.

The number of simulated background events in the $M_{t\bar{t}} > 2$ TeV region that pass the boosted selection is rather limited. To ensure a proper background modeling in the entire $M_{t\bar{t}}$ range, we merge bins in the $M_{t\bar{t}}$ distribution requiring a minimum number of background events per bin. The bins are chosen such that the uncertainty on the number of expected background events due to the limited number of simulated events is not worse than 30% in all channels. The uncertainty due to finite size of the simulated samples is taken into account using the “Barlow-Beeston lite” method [58] that defines one additional nuisance parameter with a Gaussian distribution for each bin, and performs the maximization of the likelihood with respect to these new parameters analytically.

Figures 4 and 5 show the expected and observed 95% CL upper limits for the product of the production cross section times branching fraction of hypothesized resonances that decay into $t\bar{t}$ as a function of the invariant mass of the resonance. The dashed lines indicate the values predicted by various models for new physics processes. The expected mass exclusion region for a topcolor Z' with $\Gamma_{Z'}/m_{Z'} = 1.2\%$ is $M_{Z'} < 1.53$ TeV, the observed exclusion is $M_{Z'} < 1.49$ TeV. For wide resonances with $\Gamma_{Z'}/m_{Z'} = 10\%$, the exclusion mass region is $M_{Z'} < 2.04$ TeV for both the expected and observed limits. In Fig. 4, the vertical dashed line indicates the transition between the threshold and the boosted analyses, chosen based on the sensitivity of the expected limit. For a Kaluza–Klein excitation of a gluon (g_{KK}) the exclusion mass region is $M(g_{KK}) < 1.82$ TeV for both the expected and observed limits.

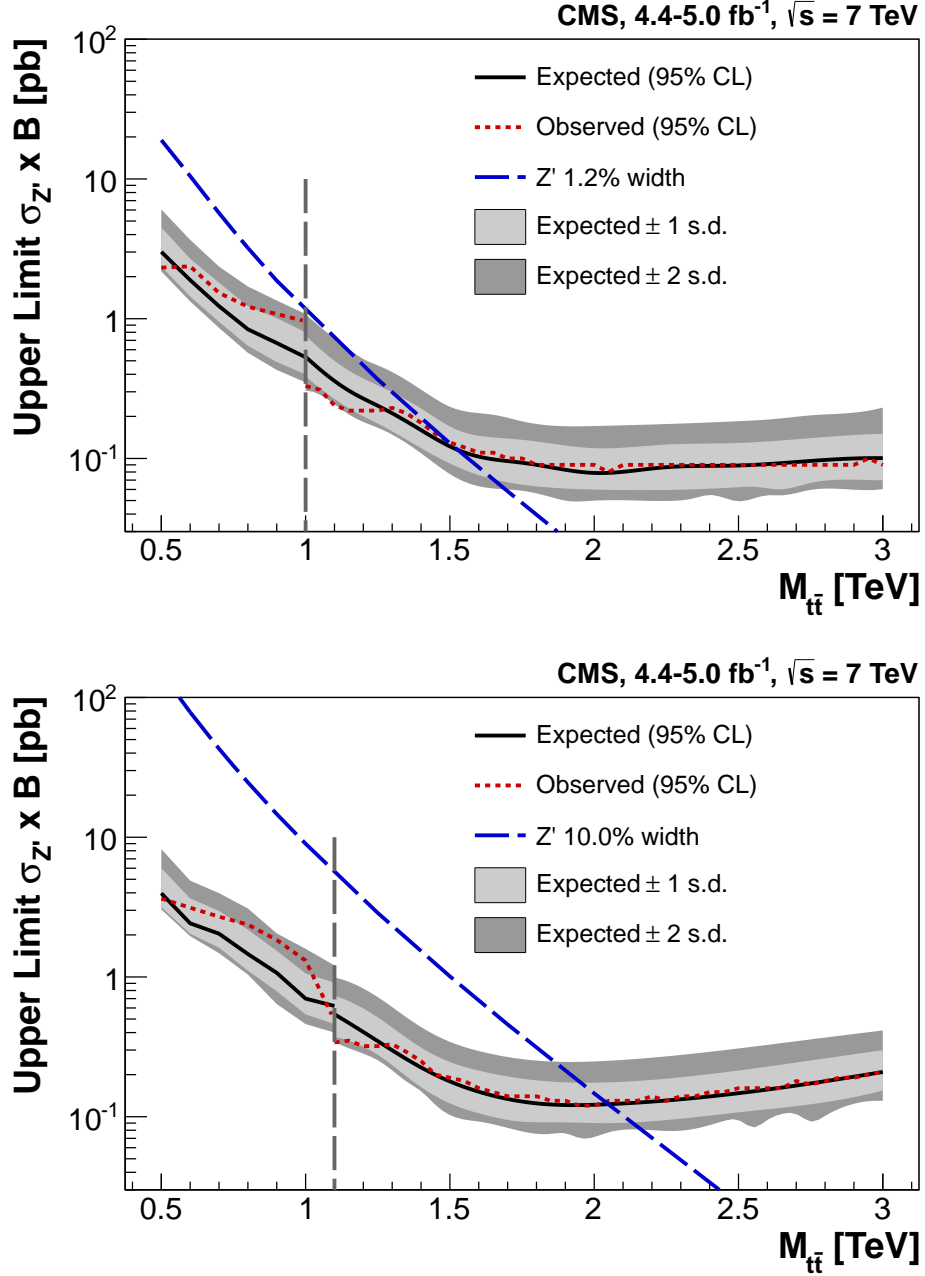


Figure 4: The 95% CL upper limits on the product of the production cross section $\sigma_{Z'}$ and the branching fraction B of hypothesized resonances that decay into $t\bar{t}$ as a function of the invariant mass of the resonance. The Z' production with $\Gamma_{Z'}/m_{Z'} = 1.2\%$ (a) and 10% (b) compared to predictions based on [5]. The ± 1 and ± 2 s.d. excursions from the expected limits are also shown. The vertical dashed line indicates the transition between the threshold and the boosted analyses, chosen based on the sensitivity of the expected limit.

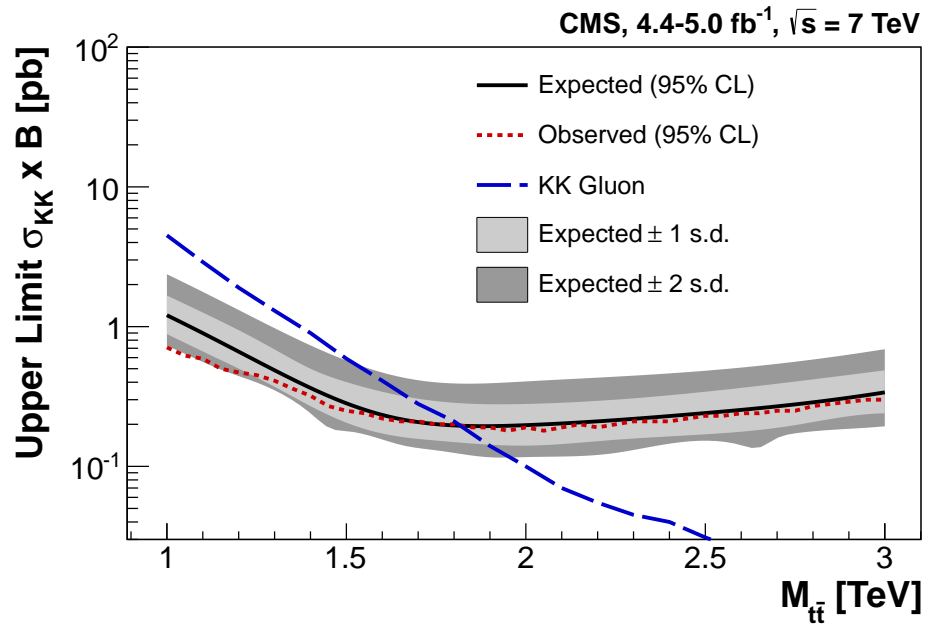


Figure 5: The 95% CL upper limits on the product of the production cross section σ_{KK} and the branching fraction B of Kaluza–Klein excitation of gluon production from [11], compared to the theoretical prediction of that model. The ± 1 and ± 2 s.d. excursions from the expected limits are also shown.

8 Summary

Results from a model-independent search for the production of heavy resonances decaying into $t\bar{t}$ are presented. The data sample corresponds to an integrated luminosity of $4.4\text{--}5.0\text{ fb}^{-1}$ recorded in 2011 by the CMS detector in pp collisions at $\sqrt{s} = 7\text{ TeV}$ at the LHC. After analyzing events with a lepton (muon or electron) plus jets final state, no evidence of such massive resonances is found above the SM prediction. Therefore, limits are set on the production of non-SM particles. Topcolor Z' bosons with a width of 1.2 (10)% of the Z' mass are excluded at 95% CL for masses below 1.49 (2.04) TeV; an upper limit of 0.3 (1.3) pb is set on the production cross section times branching fraction for a resonance mass of 1 TeV. In addition, Kaluza–Klein excitations of a gluon with masses below 1.82 TeV (at 95% CL) in the Randall–Sundrum model are excluded; an upper limit of 0.7 pb is set on the production cross section times branching fraction for a resonance mass of 1 TeV. In both instances, the upper limits are lower for larger resonance masses. These results set the most stringent limits, to date, for $t\bar{t}$ resonant production in the 0.5–2 TeV mass range.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spillbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

T.S. Anjos³, C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejjardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann⁵, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov¹⁶, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei²², H. Bakhshiansohi, S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁴, M. Zeinali

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c},

N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁵, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

P. Fabbriatore^a, R. Musenich^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, N. Cavallo^{a,26}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,26}, A.O.M. Iorio^a, L. Lista^a, S. Meola^{a,27}, M. Merola^{a,b}, P. Paolucci^{a,5}

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^{a,5}, D. Bisello^{a,b}, A. Branca^{a,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b,5}, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}, S. Taroni^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c,5}, R. Dell'Orso^a, F. Fiori^{a,b,5}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,28}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,29}, P. Spagnolo^a, P. Squillacioti^{a,5}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli, M. Grassi^{a,b,5}, E. Longo^{a,b},

P. Meridiani^{a,5}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, C. Mariotti^{a,5}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,5}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, P.P. Trapani^{a,b}, A. Vilela Pereira^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candellise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,5}, D. Montanino^{a,b,5}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³⁰, M. Djordjevic, M. Ekmedzic, D. Krpic³⁰, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez

Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³², C. Rovelli³³, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁴, D. Spiga, A. Tsiros, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁵, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁶

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁷, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁸, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tuppiti, M. Verzetti

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar⁴¹, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴², A. Polatoz, K. Sogut⁴³, D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁴, M. Kaya⁴⁵, O. Kaya⁴⁵, S. Ozkorucuklu⁴⁶, N. Sonmez⁴⁷

Istanbul Technical University, Istanbul, Turkey

K. Cankocak

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁵, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴⁸, K.W. Bell, A. Belyaev⁴⁸, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³⁸, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁴⁹, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵⁰, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵¹, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵², C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵³, G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁴, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁵, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok⁵⁶, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁷, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

S. Guragain, N. Parashar

Rice University, Houston, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Duder, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

3: Also at Universidade Federal do ABC, Santo Andre, Brazil

4: Also at California Institute of Technology, Pasadena, USA

- 5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at British University, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at National Centre for Nuclear Research, Swierk, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 26: Also at Università della Basilicata, Potenza, Italy
- 27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 31: Also at University of California, Los Angeles, Los Angeles, USA
- 32: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 33: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 34: Also at University of Athens, Athens, Greece
- 35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 36: Also at The University of Kansas, Lawrence, USA
- 37: Also at Paul Scherrer Institut, Villigen, Switzerland
- 38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 39: Also at Gaziosmanpasa University, Tokat, Turkey
- 40: Also at Adiyaman University, Adiyaman, Turkey
- 41: Also at Izmir Institute of Technology, Izmir, Turkey
- 42: Also at The University of Iowa, Iowa City, USA
- 43: Also at Mersin University, Mersin, Turkey
- 44: Also at Ozyegin University, Istanbul, Turkey
- 45: Also at Kafkas University, Kars, Turkey
- 46: Also at Suleyman Demirel University, Isparta, Turkey
- 47: Also at Ege University, Izmir, Turkey
- 48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 49: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 50: Also at University of Sydney, Sydney, Australia
- 51: Also at Utah Valley University, Orem, USA

52: Also at Institute for Nuclear Research, Moscow, Russia

53: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

54: Also at Argonne National Laboratory, Argonne, USA

55: Also at Erzincan University, Erzincan, Turkey

56: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

58: Also at Kyungpook National University, Daegu, Korea